Journal of Forensic and Legal Medicine 20 (2013) 875–883

Contents lists available at ScienceDirect

Journal of Forensic and Legal Medicine

journal homepage: www.elsevier.com/locate/jflm

Original communication

A comparison of Demirjian's four dental development methods for forensic age estimation in South Australian sub-adults

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ARTICLE INFO

Article history:
Received 6 September 2012
Accepted 22 July 2013
Available online 15 August 2013

Keywords:
Forensic odontology
Dental development
Age estimation
Population-standards
South Australia

ABSTRACT

The aim of this study was to compare the accuracy of Demirjian's four dental development methods for forensic age assessment in a South Australian population. The sample comprised orthopantomograms (OPGs) of 408 sub-adult individuals (211 male; 197 female) with an age range of 4.9–14.5 years. The OPGs were obtained from various dental schools and clinics in urban Adelaide. The following Demirjian methods were evaluated: the original 7-tooth technique; the revised 7-tooth system; the 4-tooth method; and the alternate 4-tooth approach. The left mandibular teeth in each OPG were assessed and rated according to the eight stages (A–H) defined and illustrated in Demirjian et al.[5] Differences between chronological and estimated ages were calculated for males and females separately; 95% confidence intervals of mean age differences were calculated and ANOVA used to assess the significance of mean differences.

When comparing all four methods there were significant differences overall (and in individual age groups) between mean chronological and estimated age in both sexes. In addition, each method consistently overestimated chronological age. We also demonstrate that the accuracy of the dental age methods evaluated varies in different subsets of an Australian population, a finding that parallels previous research in other global populations. Based on our analyses we conclude that population-specific standards based on dental maturity curves, as opposed to estimated ages, would provide more accurate and statistically robust age estimations.

1. Introduction

It is well established that the most accurate methods of estimating age in sub-adult individuals are based on quantifying developmental milestones in the dentition. These methods include the radiographic evaluation of tooth mineralization, calcification and root development.[1] Although there are a number of tooth formation standards currently available in the literature,[2–4] one of the most commonly applied is that of Demirjian et al.,[5] which is based on an eight-stage composite visual system of tooth developmental stages, from initial calcification of the cusps to closure of the root apex.[6,7]

The standards of Demirjian et al.[5] were developed based on the radiographic analysis of French–Canadian sub-adults, however, it is known that there is variation in the timing of dental development, both within and between populations.[8] Tests of Demirjian et al.'s[5] standards in a number of geographically and genetically removed populations have demonstrated a higher level of error than what was reported in the original study (e.g. Chinese[9]; South Indian[10]; British[6]; Northern Turkish[11]). The most accurate dental age estimates, therefore, are based on population-specific standards.[12]

Demirjian and colleagues have developed a total of four different methods of dental age estimation, all of which are based on the analysis of the left mandibular dentition, but differ in relation to the type and/or number of teeth used. These methods are: i) original 7-tooth technique (all teeth except M_3 – Demirjian et al.[5]); ii) revised 7-tooth system (same teeth but with extended age ranges and two extra stages); iii) 4-tooth method (M_2 to PM_1 inclusive); and iv) alternate 4-tooth approach (M_2, PM_2, PM_1, I_1 – Demirjian & Goldstein[13]). Demirjian et al.[5] recognized, however, that the groups of teeth studied in each of those methods might actually have their own 'distinctive developmental pattern' and thus represent a subsystem of dental maturity.[13] To-date much of the published

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http://dx.doi.org/10.1016/j.jflm.2013.07.002

literature has focused on evaluating the 7-tooth method, whereas the 4-tooth methods appear somewhat under utilized. This demonstrates the need to re-evaluate and compare all four methods.

Previous research has largely focused on comparing the accuracy of the various Demirjian methods between populations, with a lesser emphasis on comparing the accuracy of those methods within the one single population. With specific reference to Western Australia, Flood et al.[14] compared the accuracy of four Demirjian methods in a Western Australian population (age4.6–14.5 years). It was demonstrated that the 4-tooth method is the most accurate for estimating age in both males and females, as it has the lowest overall mean deviation between chronological and estimated age, and therefore, the highest accuracy. Farah et al.[15] also examined a Western Australian population and similarly determined that the 4-tooth method was accurate (no other methods were tested).

McKenna et al.[16] evaluated the accuracy of the revised 7-tooth system[13] in a South Australian population; the sample comprised 615 individuals between 4.9 and 16.9 years of age. It was concluded that the revised 7-tooth system was not suitable as South Australian sub-adults (both male and female) were less dentally advanced in earlier years, but more advanced in later years, compared to the original French–Canadian population. The accuracy of the other available systems (e.g. original 7-tooth and both 4-tooth methods) was not evaluated. In a large sample of sub-adults (1638 males & 1623 females) from Sydney, New South Wales, Blenkin and Evans[17] similarly found that the published Demirjian standards consistently overestimated chronological age (mean + 0.99 years) in individuals less than 14 years old.

Clearly there are some points of accordance between the aforementioned Western and South Australian research, whereby in both populations the revised 7-tooth system cannot be reliably applied. Although the 4-tooth method is known to be accurate in the Western Australian population,[14,15] it is not safe to assume that this would hold true for South Australia, because there are known differences in the ethnic composition of different Australian regions. For example, the Western Australian population differs from South Australia in that nearly 10% more of the former population consists of individuals born overseas.[18] There are thus also notable differences in the ethnic composition of both states because (both historically and in a modern context) different regions of the country have for specific reasons (e.g., proximity, employment opportunities) attracted immigrants from diverse geographic regions.

The main objective of the present study is, therefore, to apply Demirjian's four methods of dental age estimation to a South Australian population; the specific aim is to establish whether there are any differences between the mean chronological and estimated ages overall, and at the individual level, for each method.

2. Materials and methods

2.1. Materials

The present study examines orthopantomograms (OPGs) of 408 individuals; 211 males and 197 females with an age range of 4.9–14.5 years. The OPGs were obtained from various dental school clinics of the South Australian Dental Service, the Adelaide Dental Hospital, the Orthodontic Clinic, and private orthodontic practices in urban areas of Adelaide. The chronological age of each individual was calculated by subtracting the date of birth from the date the radiograph was taken; this was then converted to years and months, where months is established as a fraction of 12.0 months (e.g., 7.0 years and 10.0 months is expressed as 7.8 years). The sample is arranged into 10 age groups (from 5 to 14 years) with each containing an associated age-range; for example, age group 6 denotes individuals from 5.6 to 6.5 years of age.

The OPGs were chosen from a mostly homogeneous sample of South Australian individuals. Questionnaires were used to obtain information relating to the birthplace of both the subject and their parents. Of the 211 male individuals, 172 were Australian-born, of which 129 had Australian-born parents; for the 197 female individuals, 159 were Australian-born and of those 115 had Australian-born parents. Individuals with pre-existing medical conditions, congenital defects, and/or missing teeth were excluded from the study. Those individuals with a total maturity score of 100 (e.g., a 'perfect' maturity score) were also not included as Demirjian et al.'s[5] conversion chart of maturity score to dental age only extends to 98.4 for males, on this basis all females with dental maturity scores of 100 were also removed (see below). Ethics approval to undertake the project was granted by the Human Research Ethics Committee at The University of Western Australia (RA/4/1/1949).

2.2. Methods

2.2.1. Data acquisition

The applicability and accuracy of the following Demirjian methods are evaluated in the South Australian sample: the original 7-tooth technique (M_2, M_1, PM_2, PM_1, C, I_2, I_1); the revised 7-tooth system (M_2, M_1, PM_2, PM_1, C, I_2, I_1); the 4-tooth method

Table 1
A comparison of mean chronological and estimated ages for South Australian males using the original 7-tooth technique of Demirjian et al.[5]

Males	Mean		Original 7			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.10 (NA)	5.00 (NA)	−0.10 (0.95)	(−1.972, 1.772)	−0.105 (201)	0.916
6 (2)	6.20 (0.28)	7.15 (0.07)	0.95 (0.67)	(−0.374, 2.274)	1.415 (201)	0.159
7 (24)	7.16 (0.25)	7.85 (0.43)	0.69 (0.19)	(0.305, 1.070)	3.548 (201)	0.000[e]
8 (35)	8.05 (0.29)	8.53 (0.75)	0.48 (0.16)	(0.166, 0.799)	3.009 (201)	0.003[e]
9 (45)	9.10 (0.28)	9.85 (1.08)	0.75 (0.14)	(0.468, 1.026)	5.276 (201)	0.000[e]
10 (35)	10.05 (0.28)	10.52 (0.96)	0.47 (0.16)	(0.155, 0.788)	2.938 (201)	0.004[e]
11 (31)	11.11 (0.29)	11.63 (0.97)	0.52 (0.17)	(0.183, 0.856)	3.046 (201)	0.003[e]
12 (18)	12.12 (0.31)	13.13 (1.23)	1.01 (0.22)	(0.570, 1.452)	4.518 (201)	0.000[e]
13 (13)	13.02 (0.36)	13.38 (1.49)	0.36 (0.26)	(−0.158, 0.881)	1.373 (201)	0.171
14 (7)	13.97 (0.40)	14.66 (1.32)	0.69 (0.36)	(−0.022, 1.393)	1.911 (201)	0.057
(211)	9.77 (1.91)	10.38 (2.14)	0.61 (0.06)	(0.483, 0.740)	9.390 (201)	2.2×10^{-16}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; *t* – ratio of the mean age difference and its estimated standard error.

Table 2
A comparison of mean chronological and estimated ages for South Australian males using the revised 7-tooth system of Demirjian and Goldstein.[13]

Males	Mean		Revised 7			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.10 (NA)	4.50 (NA)	−0.60 (0.92)	(−2.415, 1.215)	−0.652 (201)	0.515
6 (2)	6.20 (0.28)	6.95 (0.07)	0.75 (0.65)	(−0.533, 2.033)	1.153 (201)	0.250
7 (24)	7.16 (0.25)	7.70 (0.46)	0.55 (0.19)	(0.175, 0.916)	2.906 (201)	0.004[e]
8 (35)	8.05 (0.29)	8.45 (0.76)	0.40 (0.16)	(0.090, 0.704)	2.553 (201)	0.011[e]
9 (45)	9.10 (0.28)	9.79 (1.05)	0.69 (0.14)	(0.418, 0.959)	5.022 (201)	0.000[e]
10 (35)	10.05 (0.28)	10.45 (0.94)	0.39 (0.16)	(0.088, 0.701)	2.535 (201)	0.012[e]
11 (31)	11.11 (0.29)	11.55 (1.05)	0.45 (0.17)	(0.123, 0.774)	2.713 (201)	0.007[e]
12 (18)	12.12 (0.31)	12.94 (1.18)	0.82 (0.22)	(0.395, 1.250)	3.791 (201)	0.000[e]
13 (13)	13.02 (0.36)	13.11 (1.27)	0.09 (0.26)	(−0.419, 0.588)	0.332 (201)	0.741
14 (7)	13.97 (0.40)	14.20 (1.05)	0.23 (0.35)	(−0.457, 0.914)	0.657 (201)	0.512
(211)	9.77 (1.91)	10.26 (2.09)	0.49 (0.06)	(0.368, 0.618)	7.769 (201)	3.4×10^{-13}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; t – ratio of the mean age difference and its estimated standard error.

(M_2, M_1, PM_2, PM_1); and the alternate 4-tooth approach (M_2, PM_2, PM_1, I_1). The left mandibular teeth in each OPG were assessed and rated according to the eight stages (A–H) defined and illustrated in Demirjian et al.[5] Sex-specific numerical scores are assigned to each individual tooth; these are summed to acquire a total maturity score out of 100. The total maturity scores are then converted to an estimated age using either a conversion table for the original 7-tooth technique,[5] or maturity percentile curves at the 50th percentile for the remaining methods.[13]

2.2.2. Statistical analyses – group differences

Age differences were determined by subtracting estimated age from chronological age, and the accuracy was defined as how closely the age estimates could be correlated with chronological age. Differences between chronological and estimated ages (for all four Demirjian methods) were calculated for males and females separately; 95% confidence intervals of the mean age differences were then calculated and an Analysis of Variance (ANOVA) was performed to determine the significance of the mean difference between chronological and estimated ages in the 10 age groups. Paired *t*-tests were also used to quantify the statistical significance of the overall difference between the mean chronological and estimated ages in each sex for all four methods.

2.2.3. Statistical analyses – individual differences

For all four methods differences at the individual level were evaluated by subtracting chronological age from estimated age in order to yield minimum (largest underestimate) and maximum (largest overestimate) differences; overall mean age deviations were determined by averaging these individual differences. Quartiles were calculated, which are the values that divide the sample into four equal groups, with each representing one-quarter of the total sample.[19] The 1st (lower quartile; 25th percentile) and 3rd (upper quartile; 75th percentile) quartiles were determined in order to concentrate on the data in the middle of the sample, as opposed to the data at both ends of the spectrum (i.e., below the 25th percentile or above the 75th percentile). All statistical analyses were performed using R, version 2.11.0 (Vienna, Austria, 2010).

3. Results

3.1. Males

3.1.1. Group differences

Mean estimated ages were compared with mean chronological ages for each age group (5–14 years) for all four methods (Tables 1–4). *Post-hoc* comparisons of differences in means showed

Table 3
A comparison of mean chronological and estimated ages for South Australian males using the 4-tooth method of Demirjian and Goldstein.[13]

Males	Mean		4-Tooth			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.10 (NA)	5.60 (NA)	0.50 (0.92)	(−1.311, 2.311)	0.545 (201)	0.587
6 (2)	6.20 (0.28)	7.00 (0.00)	0.80 (0.65)	(−0.480, 2.080)	1.232 (201)	0.219
7 (24)	7.16 (0.25)	7.74 (0.59)	0.58 (0.19)	(0.214, 0.953)	3.112 (201)	0.002[e]
8 (35)	8.05 (0.29)	8.37 (0.71)	0.32 (0.16)	(0.017, 0.629)	2.080 (201)	0.039[e]
9 (45)	9.10 (0.28)	9.56 (1.04)	0.46 (0.14)	(0.192, 0.732)	3.377 (201)	0.001[e]
10 (35)	10.05 (0.28)	10.12 (1.00)	0.07 (0.16)	(−0.240, 0.372)	0.423 (201)	0.672
11 (31)	11.11 (0.29)	11.33 (0.91)	0.22 (0.17)	(−0.103, 0.548)	1.350 (201)	0.179
12 (18)	12.12 (0.31)	12.72 (1.16)	0.61 (0.22)	(0.179, 1.032)	2.798 (201)	0.006[e]
13 (13)	13.02 (0.36)	12.79 (1.42)	−0.23 (0.26)	(−0.733, 0.271)	−0.906 (201)	0.366
14 (7)	13.97 (0.40)	14.10 (1.21)	0.13 (0.35)	(−0.556, 0.813)	0.370 (201)	0.711
(211)	9.77 (1.91)	10.08 (2.02)	0.31 (0.06)	(0.188, 0.440)	4.912 (201)	1.8×10^{-6}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; t – ratio of the mean age difference and its estimated standard error.

Table 4
A comparison of mean chronological and estimated ages for South Australian males using the alternate 4-tooth approach of Demirjian and Goldstein.[13]

Males	Mean		Alternate 4			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.10 (NA)	5.00 (NA)	−0.10 (0.93)	(−1.939, 1.739)	−0.107 (201)	0.915
6 (2)	6.20 (0.28)	7.00 (0.00)	0.80 (0.66)	(−0.500, 2.100)	1.213 (201)	0.227
7 (24)	7.16 (0.25)	7.75 (0.73)	0.59 (0.19)	(0.212, 0.963)	3.086 (201)	0.002[e]
8 (35)	8.05 (0.29)	8.58 (0.93)	0.53 (0.16)	(0.223, 0.845)	3.389 (201)	0.001[e]
9 (45)	9.10 (0.28)	9.83 (1.09)	0.73 (0.14)	(0.457, 1.005)	5.259 (201)	0.000[e]
10 (35)	10.05 (0.28)	10.42 (1.03)	0.37 (0.16)	(0.058, 0.679)	2.338 (201)	0.020[e]
11 (31)	11.11 (0.29)	11.56 (0.85)	0.46 (0.17)	(0.125, 0.785)	2.715 (201)	0.007[e]
12 (18)	12.12 (0.31)	12.79 (1.01)	0.67 (0.22)	(0.239, 1.106)	3.058 (201)	0.003[e]
13 (13)	13.02 (0.36)	12.80 (1.20)	−0.22 (0.26)	(−0.733, 0.287)	−0.862 (201)	0.390
14 (7)	13.97 (0.40)	13.89 (1.06)	−0.09 (0.35)	(−0.781, 0.609)	−0.243 (201)	0.808
(211)	9.77 (1.91)	10.26 (2.00)	0.49 (0.06)	(0.359, 0.616)	7.472 (201)	2.1×10^{-12}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; t – ratio of the mean age difference and its estimated standard error.

that for both 7-tooth methods and the alternate 4-tooth approach, six out of the 10 age groups have a significant difference between mean chronological and estimated ages (groups 7–12 in each – Tables 1–2 & 4). The 4-tooth method has the least number of significantly different age groups (four out of 10; groups 7–9 and 12 – Table 3).

In considering the mean data of the 10 age groups, it is evident that all four methods overall resulted in statistically significant differences between chronological and estimated age: original 7-tooth ($t = 9.390$; $p = 2.2 \times 10^{-16}$); revised 7-tooth ($t = 7.769$; $p = 3.4 \times 10^{-13}$); 4-tooth ($t = 4.912$; $p = 1.8 \times 10^{-6}$); and alternate 4-tooth ($t = 4.720$; $p = 2.1 \times 10^{-12}$). When overall mean age

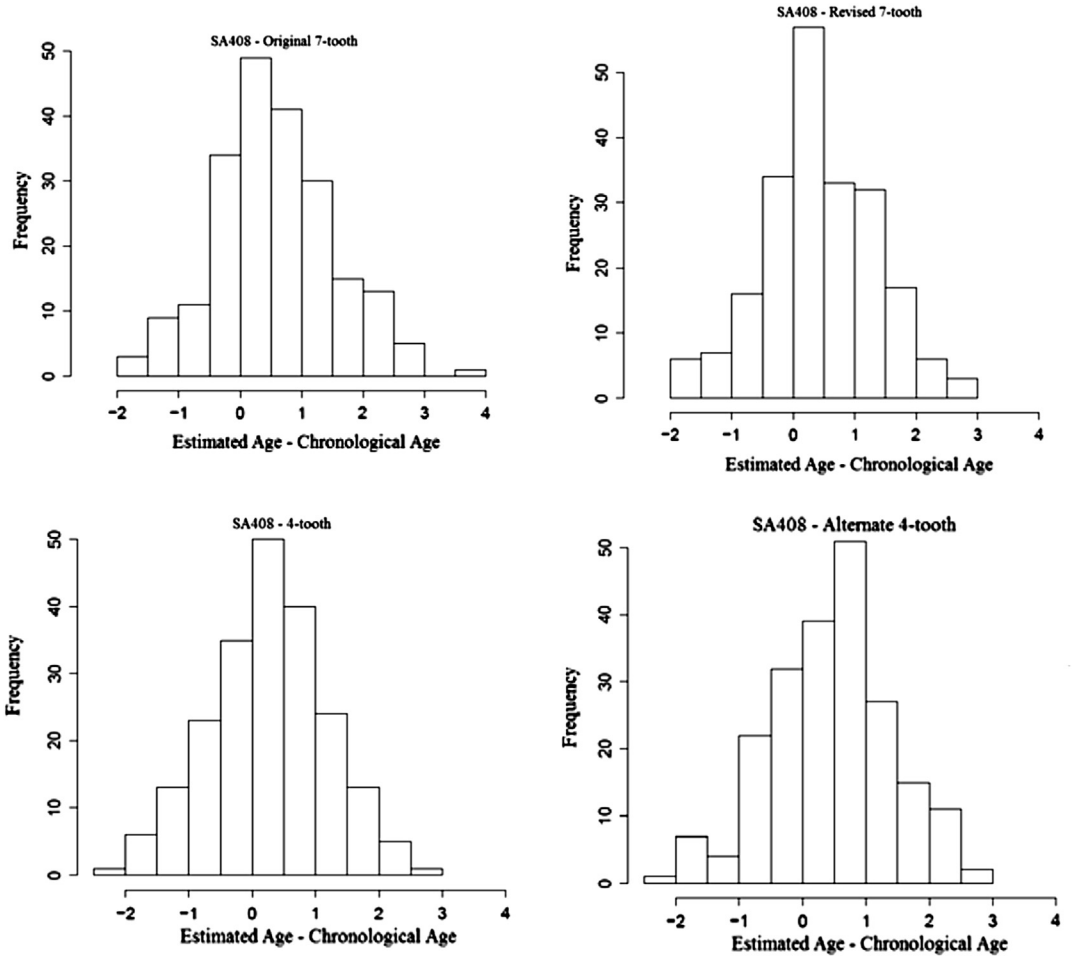

Fig. 1. Individual differences for the South Australian sample of males using all four Demirjian methods.

deviations were calculated, the 4-tooth method has the smallest absolute difference (0.31 years; SE = 0.06) and the original 7-tooth technique had the largest difference (0.61 years; SE = 0.06). The revised 7-tooth and alternate 4-tooth approach both had a mean age difference of 0.49 years.

3.1.2. Individual differences

The maximum and minimum deviations for any one individual for all four methods are shown in Fig. 1. For all methods (except alternate 4-tooth) the individual difference between chronological and estimated age was most frequently within 0 to +0.5 years (overestimation). For the 4-tooth method the age of the majority of individuals was over-estimated by 0.5–1 year (Fig. 1). For the original 7-tooth technique the largest underestimate and overestimate was 2.0 and 3.6 years respectively (1st quartile = 0.000; mean = 0.612; 3rd quartile = 1.200). The revised 7-tooth system had deviation values of 2.0 and 2.8 years respectively (1st quartile = −0.100; mean = 0.493; 3rd quartile = 1.100). For the 4-tooth method the largest underestimate and overestimate values were 2.5 and 2.7 years respectively (1st quartile = −0.300; mean = 0.314; 3rd quartile = 0.900). Comparable figures for the alternate 4-tooth approach are 2.4 and 2.7 years (1st quartile = −0.200; mean = 0.487; 3rd quartile = 1.100).

3.2. Females

3.2.1. Group differences

Comparisons of mean estimated and chronological ages for each of the four methods in females are shown in Tables 5–8. For the original 7-tooth and alternate 4-tooth approach, *Post-hoc* comparisons of mean deviations were significant for seven out of 10 cases (individual age groups 7–13; Tables 5 and 8). A total of seven groups were also significantly different for the revised 7-tooth system (individual age groups 7–12 & 14; Table 6). The 4-tooth method had the least number of significantly different comparisons (individual groups 7–8 and 11–13; Table 7).

With regard to the mean data of all 10 age groups, it is apparent that all four methods significantly overestimate chronological age: original 7-tooth technique ($t = 10.969$; $p = 2.2 \times 10^{-16}$); revised 7-tooth system ($t = 7.368$; $p = 4.7 \times 10^{-12}$); 4-tooth method ($t = 7.921$; $p = 1.7 \times 10^{-13}$); alternate 4-tooth approach ($t = 8.966$; $p = 2.4 \times 10^{-16}$). Overall mean age deviations are largest for the original 7-tooth technique (0.75 years; SE = 0.07) and the smallest deviation was for the revised 7-tooth system (0.47 years; SE = 0.06). The deviation for the 4-tooth method is the next smallest (0.62 years; SE = 0.08) and the associated values for the alternate 4-tooth approach are 0.70 years with an SE of 0.08.

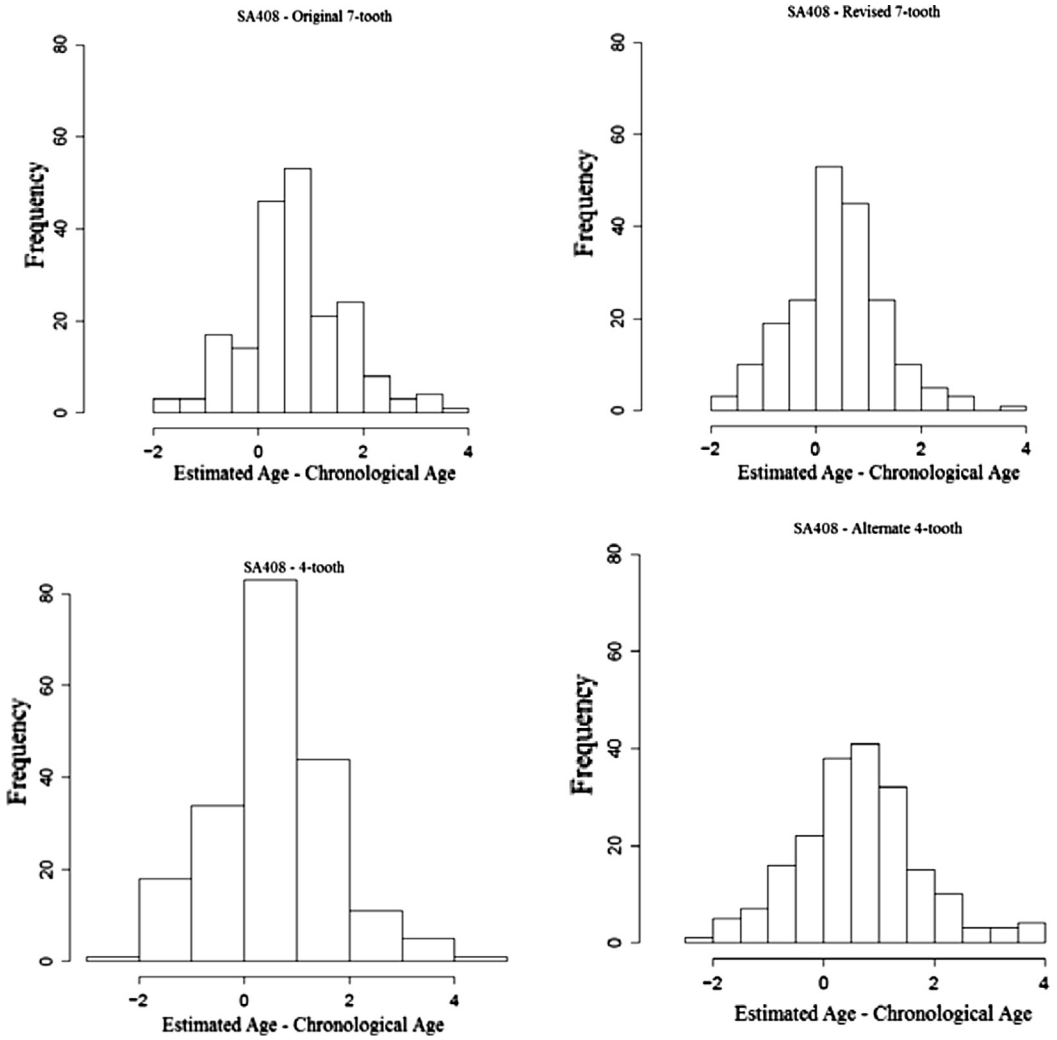

Fig. 2. Individual differences for the South Australian sample of females using all four Demirjian methods.

Table 5
A comparison of mean chronological and estimated ages for South Australian females the original 7-tooth technique of Demirjian et al.[5]

Females	Mean		7-Tooth			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.50 (NA)	6.30 (NA)	0.80 (0.93)	(−1.042, 2.642)	0.857 (187)	0.393
6 (2)	5.95 (0.07)	7.10 (0.71)	1.15 (0.66)	(−0.153, 2.453)	1.741 (187)	0.083
7 (19)	7.12 (0.23)	8.02 (0.58)	0.91 (0.21)	(0.483, 1.328)	4.225 (187)	0.000[e]
8 (29)	8.11 (0.26)	8.78 (0.44)	0.68 (0.17)	(0.334, 1.018)	3.897 (187)	0.000[e]
9 (30)	9.06 (0.28)	9.57 (1.02)	0.51 (0.17)	(0.177, 0.850)	3.011 (187)	0.003[e]
10 (35)	10.05 (0.29)	10.64 (1.11)	0.59 (0.16)	(0.283, 0.906)	3.765 (187)	0.000[e]
11 (30)	11.12 (0.31)	12.22 (1.37)	1.10 (0.17)	(0.767, 1.440)	6.471 (187)	0.000[e]
12 (23)	12.07 (0.27)	13.15 (1.10)	1.08 (0.20)	(0.698, 1.467)	5.559 (187)	0.000[e]
13 (17)	13.04 (0.24)	13.92 (0.84)	0.88 (0.23)	(0.436, 1.329)	3.895 (187)	0.000[e]
14 (11)	14.15 (0.39)	14.05 (0.78)	−0.10 (0.28)	(−0.656, 0.456)	−0.355 (187)	0.723
(197)	10.15 (2.06)	10.90 (2.27)	0.75 (0.07)	(0.616, 0.886)	10.970 (187)	2.2×10^{-16}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; *t* – ratio of the mean age difference and its estimated standard error.

3.2.2. Individual differences

Individual maximum and minimum deviations for all four methods are shown in Fig. 2. For the revised 7-tooth and 4-tooth approach it is evident that the majority individuals (>80% in the latter method) were overestimated by between 0 and 0.5 years. For the original 7-tooth technique and revised 4-tooth system, the majority of individuals are overestimated by between 0.5 and 1 year (Fig. 2). For the original 7-tooth technique the largest underestimate and overestimate was 1.7 and 3.8 years respectively (1st quartile = 0.200; mean = 0.751; 3rd quartile = 1.300). Comparable figures for the revised 7-tooth system are 1.8 and 3.6 years respectively (1st quartile = 0.000; mean = 0.468; 3rd quartile = 1.000). For the original 4-tooth method the largest underestimate and overestimate were 2.1 and 4.3 years respectively (1st quartile = 0.000; mean = 0.622; 3rd quartile = 1.300). For the alternate 4-tooth approach largest underestimate and overestimate was 2.2 and 4.0 years respectively (1st quartile = 0.000; mean = 0.704; 3rd quartile = 1.400).

4. Discussion

An important consideration in the forensic sciences, especially those disciplines pertaining to human identification, is the level of confidence in, and accuracy of, the final estimation. With regard to the accuracy of dental age estimation in juvenile individuals, various published studies consistently demonstrate accuracy rates of $\leq \pm 3$ years, with the highest accuracy achievable in younger individuals.[20,21] One must consider, however, the inherent influence of individual variation in tooth development, which as Mornstad et al., noted, "…is about ±1.5–2.0 yr at the 95% level."[22] Those authors thus caution that it is not possible to estimate the age of a sub-adult more precisely. There is also the issue of regional variability, which means that the 'natural' level of variation in the timing of dental development found within populations is likely to be smaller than the level of variation found between populations.[8,20,22,23] This, in essence, highlights the importance of population-specific standards, although there are suggestions that such standards are not necessarily required.[24]

In the evaluating the suitability of applying Demirjian's methods in a South Australian population, it was found that there was an overall significant difference between mean chronological and estimated age for all four methods in both sexes. Even when examining the differences in the individual age groups, it was evident that the majority were significantly different (irrespective of sex) for all four methods. A point of commonality, however, is that the 4-tooth method has the least number of significantly

Table 6
A comparison of mean chronological and estimated ages for South Australian females using the revised 7-tooth system of Demirjian and Goldstein.[13]

Females	Mean		Revised 7-tooth			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.50 (NA)	5.70 (NA)	0.20 (0.83)	(−1.444, 1.844)	0.240 (187)	0.811
6 (2)	5.95 (0.07)	6.60 (0.85)	0.65 (0.59)	(−0.513, 1.813)	1.103 (187)	0.272
7 (19)	7.12 (0.23)	7.82 (0.65)	0.71 (0.19)	(0.328, 1.083)	3.688 (187)	0.000[e]
8 (29)	8.11 (0.26)	8.71 (0.45)	0.60 (0.16)	(0.295, 0.905)	3.876 (187)	0.000[e]
9 (30)	9.06 (0.28)	9.45 (0.96)	0.39 (0.15)	(0.090, 0.690)	2.563 (187)	0.011[e]
10 (35)	10.05 (0.29)	10.45 (1.08)	0.41 (0.14)	(0.131, 0.687)	2.900 (187)	0.004[e]
11 (30)	11.12 (0.31)	11.96 (1.17)	0.84 (0.15)	(0.536, 1.137)	5.498 (187)	0.000[e]
12 (23)	12.07 (0.27)	12.72 (0.85)	0.65 (0.17)	(0.309, 0.995)	3.752 (187)	0.000[e]
13 (17)	13.04 (0.24)	13.18 (0.58)	0.14 (0.20)	(−0.258, 0.540)	0.698 (187)	0.486
14 (11)	14.15 (0.39)	13.36 (0.45)	−0.78 (0.25)	(−1.278, −0.286)	−3.111 (187)	0.002[e]
(197)	10.15 (2.06)	10.62 (2.08)	0.47 (0.06)	(0.343, 0.593)	7.368 (187)	4.7×10^{-12}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; *t* – ratio of the mean age difference and its estimated standard error.

Table 7
A comparison of mean chronological and estimated ages for South Australian females using the 4-tooth method of Demirjian and Goldstein.[13]

Females	Mean		4-Tooth			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.50 (NA)	6.00 (NA)	0.50 (1.09)	(−1.652, 2.652)	0.458 (187)	0.647
6 (2)	5.95 (0.07)	6.80 (0.99)	0.85 (0.77)	(−0.672, 2.372)	1.102 (187)	0.272
7 (19)	7.12 (0.23)	7.99 (0.67)	0.88 (0.25)	(0.385, 1.373)	3.512 (187)	0.001[e]
8 (29)	8.11 (0.26)	8.66 (0.37)	0.56 (0.20)	(0.156, 0.955)	2.740 (187)	0.007[e]
9 (30)	9.06 (0.28)	9.37 (1.07)	0.32 (0.20)	(−0.076, 0.710)	1.590 (187)	0.114
10 (35)	10.05 (0.29)	10.39 (1.21)	0.35 (0.18)	(−0.015, 0.712)	1.890 (187)	0.060
11 (30)	11.12 (0.31)	12.04 (1.47)	0.92 (0.20)	(0.524, 1.310)	4.602 (187)	0.000[e]
12 (23)	12.07 (0.27)	13.02 (1.46)	0.95 (0.23)	(0.503, 1.401)	4.186 (187)	0.000[e]
13 (17)	13.04 (0.24)	13.92 (1.25)	0.88 (0.27)	(0.360, 1.404)	3.335 (187)	0.001[e]
14 (11)	14.15 (0.39)	14.28 (0.97)	0.14 (0.33)	(−0.513, 0.785)	0.415 (187)	0.679
(197)	10.15 (2.06)	10.77 (2.37)	0.62 (0.08)	(0.467, 0.777)	7.921 (187)	1.7×10^{-13}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; t – ratio of the mean age difference and its estimated standard error.

different age groups (5 out of 10) in both sexes. The latter information at face value suggests that one must be cautious when considering applying any of the four Demirjian methods to a South Australian population, however, the actual magnitude of the difference between estimated and chronological age must also be accordingly considered.

When determining overall age estimates for males and females, all four methods consistently overestimate chronological age, with the original 7-tooth technique consistently yielding the highest overestimate. With regard to the lowest overestimate, males and females showed differing results; the 4-tooth method yielded the lowest overestimate in males, while it had the second lowest overestimate in females. When considering the accuracy of the four methods it appears that overall the original 7-tooth technique is the least accurate in both sexes and as a result should not be applied.

For practical purposes it is important to determine an individual age difference in addition to overall mean age deviations. Differences at the individual level are necessary when the dental remains of an individual are recovered and an age estimate is required. For all methods (except the alternate 4-tooth approach) the individual differences between chronological and estimated age were most frequently within 0 to +0.5 years in males, whereas for females the revised 7-tooth system and alternate 4-tooth approach resulted in the majority of individuals being overestimated by 0–0.5 years, while the minority of individuates were overestimated between 0.5 and 1 year for the other two methods. The results described above for the South Australian sample are similar to the accuracy achieved in a Western Australian population.[25]

In Flood et al.[14] it was found that when the 4-tooth method was applied to a Western Australian population, there was no statistically significant evidence for an overall difference between the mean chronological and estimated ages for either sex (males $p = 0.792$; females $p = 0.105$). When examining the differences in individual age groups for the 4-tooth method, there were no differences at any age group for the males, however there were significant differences at the individual age groups of 8.0 ($p = 0.021$) and 10.0 ($p = 0.001$) for females. These results imply that the 4-tooth method is clearly accurate in Western Australian sub-adult population, but largely inaccurate when applied to South Australian individuals.

Contrary to the data derived from the evaluation of the 4-tooth method in the South Australian population (see above), no significant differences were observed overall between the mean chronological and estimated ages with the application of the revised 7-tooth system ($p = 0.150$), the 4-tooth method ($p = 0.792$) and the alternate 4-tooth approach ($p = 0.188$) with the Western

Table 8
A comparison of mean chronological and estimated ages for South Australian females using the alternate 4-tooth approach of Demirjian and Goldstein.[13]

Females	Mean		Alternate 4-tooth			
Age[a] (*n*)	Chron[b] (SD)	Est[c] (SD)	Age diff.[d] (SE)	95% CI	*t* (dof)	Sig.[e]
5 (1)	5.50 (NA)	6.20 (NA)	0.70 (1.09)	(−1.455, 2.855)	0.641 (187)	0.522
6 (2)	5.95 (0.07)	7.00 (1.27)	1.05 (0.77)	(−0.474, 2.574)	1.359 (187)	0.176
7 (19)	7.12 (0.23)	8.26 (0.62)	1.14 (0.25)	(0.648, 1.637)	4.557 (187)	0.000[e]
8 (29)	8.11 (0.26)	8.84 (0.36)	0.73 (0.20)	(0.331, 1.131)	3.603 (187)	0.000[e]
9 (30)	9.06 (0.28)	9.53 (0.93)	0.48 (0.20)	(0.083, 0.870)	2.390 (187)	0.018[e]
10 (35)	10.05 (0.29)	10.46 (1.14)	0.42 (0.19)	(0.053, 0.781)	2.259 (187)	0.025[e]
11 (30)	11.12 (0.31)	12.01 (1.52)	0.89 (0.20)	(0.493, 1.280)	4.445 (187)	0.000[e]
12 (23)	12.07 (0.27)	12.97 (1.52)	0.90 (0.23)	(0.451, 1.349)	3.951 (187)	0.000[e]
13 (17)	13.04 (0.24)	13.94 (1.38)	0.90 (0.27)	(0.377, 1.423)	3.397 (187)	0.001[e]
14 (11)	14.15 (0.39)	14.27 (1.09)	0.13 (0.33)	(−0.523, 0.777)	0.386 (187)	0.700
(197)	10.15 (2.06)	10.85 (2.29)	0.70 (0.08)	(0.549, 0.858)	8.966 (187)	2.4×10^{-16}[e]

[a] Age group.
[b] Chronological age.
[c] Estimated age.
[d] Estimated age minus chronological age.
[e] Significance level $p < 0.05$; SD – standard deviation; SE – standard error; CI – confidence interval; dof – degrees of freedom; t – ratio of the mean age difference and its estimated standard error.

Australian males, however there were some differences noted at certain age groups.[14] With regard to the original 7-tooth technique, significant differences were noted overall in males ($p = 8.68 \times 10^{-5}$) as well as at certain individual age groups. The latter results are similar to the South Australian data analyzed in the present study, which combined adds further support that this method is inaccurate for multiple regions (and populations) within Australia. The Western Australian females, however, were not dissimilar to the South Australian females when applying the original 7-tooth technique ($p = 9.01 \times 10^{-5}$), the revised 7-tooth system ($p = 0.006$) and the alternate 4-tooth approach ($p = 0.019$).

In consideration of the results of the present study (see above) and our previous research in a Western Australian population,[14,25] it is apparent that, with regard to which of the four Demirjian methods is most accurate, there are differences between the two populations and within and between the sexes. For example, the 4-tooth method and the alternate 4-tooth approach were accurate for Western Australian males, but these methods were shown in the present study to present an unacceptably high level of inaccuracy in South Australian males. This highlights the importance of ascertaining the suitability of a particular method for application in a specific population according to sex (see below). This also reinforces the well-established notion that the most accurate age estimations will be achieved when sex-specific data are applied,[9,22] albeit accurately estimating sex in the isolated dentition is somewhat unreliable and in such situations pooled sex standards provide an appropriate alternative.

This study has established that the accuracy of different dental age methods varies in different subsets of an Australian population. This is potentially related to ethnic diversity between the Western Australian and South Australian populations; individuals of a shared genetic heritage and/or closer genetic relationship will have some degree of commonality in the timing of dental development. The latter has been described in other Australian studies, for example Blenkin and Evans[17] and McKenna et al.[16] examined subadult individuals from New South Wales and South Australia (respectively) and found Demirjian's standards to be inaccurate. Other studies that have examined subsets of populations from within the same country have revealed similar results. Prabhakar et al.[26] found that the original 7-tooth technique was inaccurate in a population of sub-adults (aged 6.0–15.0 years) from Davangere (Southern India), whereas Rai et al.[27] found the same method was accurate in a Northern Indian (Haryana) sub-adult (6.0–17.0 years) population. This indicates that different subsets of the same population can generate differing results; the specific reasoning for this apparent regional variation is unknown, but it may be related to the combined interactions of genetic, environmental, socio-economic and/or nutritional influences.[10,28]

In this study, the relationship between chronological age and estimated age was examined for a South Australian population, however other studies have examined the relationship between maturity scores and chronological age. A higher accuracy was obtained with the latter as dental maturity curves can be created based on the population being investigated as opposed to age estimates derived from Demirjian's initial French–Canadian sample.[12,29] The investigation of this phenomenon is currently progressing and the results will be the topic of a forthcoming publication.

5. Conclusion

The primary objective of the present study was to compare mean deviations between estimated and chronological age, derived from the application of the four published methods of Demirjian, in a South Australian population. The main aim was to evaluate the accuracy of those methods and thus assess their potential forensic utility for estimating age in unidentified human remains. It was demonstrated that all four methods in both males and females are relatively inaccurate for forensic age estimation. However, in the absence of a suitable alternative approach, and based on the results of this study, the Demirjian and Goldstein[13] 4-tooth method could be applied, until such time that population-specific standards based on dental maturity curves (as opposed to estimated ages) are made available.

Ethical approval

Ethics approval to undertake the project was granted by the Human Research Ethics Committee at The University of Western Australia (RA/4/1/1949).

Funding

None.

Conflict of interest

None.

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